

Plasma aerodynamic experiments

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1. Introduction

As it is well known plasma technologies nowadays find wide applications in aerodynamics, and it has become evident that development of hypersonic aviation is unlikely possible without application of plasma- and beam technologies.

In external aerodynamics they can be applied for drag and wave reduction and improvement of aircraft maneuverability.

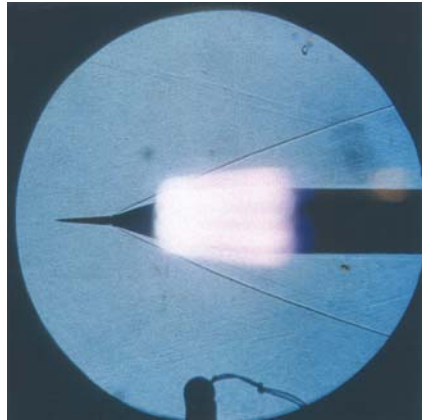
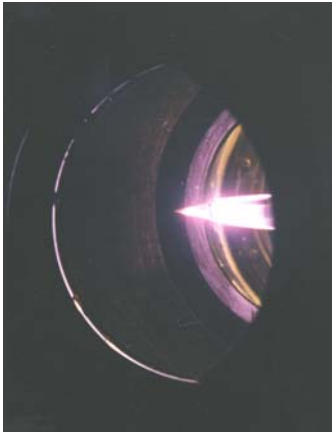
Plasma technologies in internal aerodynamics can be applied for improvement of combustion processes due to usage of created volumetric plasma structures in the stagnation zone and directly in subsonic and supersonic air-fuel mixtures. Electrical gas discharges are promising methods of combustion improvement because of their ability to produce concentrated zones with high content of chemical active species.

Actually this puts the problem of understanding the nontrivial interaction of hydrodynamic, chemical and plasma-chemical phenomena.

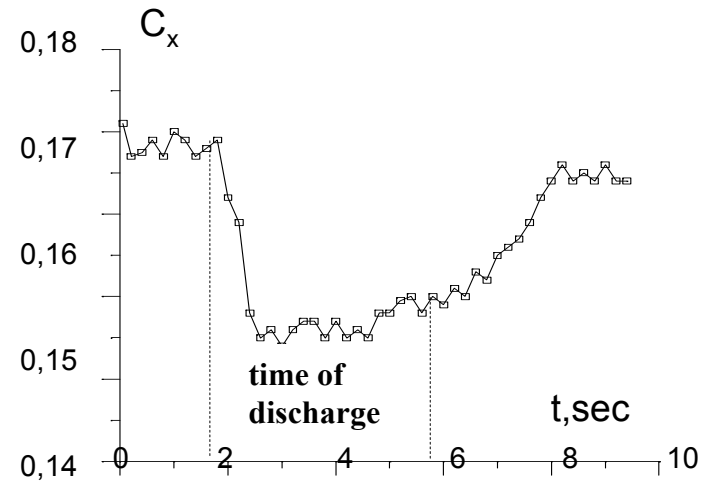
So there is absolute necessity for detailed physical study, both experimental and theoretical, of discharge activated reacting flows at well-defined conditions.

1. Introduction (continuation)

Example of Plasma dynamics technologies in aerodynamic (MTK, TsAGI and MSU)



Flow around body with presence of gaseous discharge



**Drag coefficient temporal dependence.
Mach number $M = 4$.**

1. Introduction (continuation)

Tasks :

External aerodynamics

Investigation of plasma dynamic structures interaction with high-speed flows:

- **Sources of plasma – pulsed or stationary**
- **Plasma penetration into the flow**
- **Mass-weight and energy limitations**
- **Plasma lifetime in supersonic flow**
- **Plasma influencing on the flow structure**

Internal aerodynamics

- **Shortening of induction and mixing time**
- **Sources of plasma – pulsed or stationary**
- **Plasma influencing on the air-fuel flow structure**
- **Mass-weight and energy limitations**
- **Plasma lifetime in supersonic flow**

Development of diagnostics methods

1. Introduction (continuation)

External aerodynamics (prospective directions of investigations):

- sliding discharge for angle of attack change;
- thermal spike for wave drag reduction of vehicle.
- external burning for the lift change using plasmadynamics igniters.

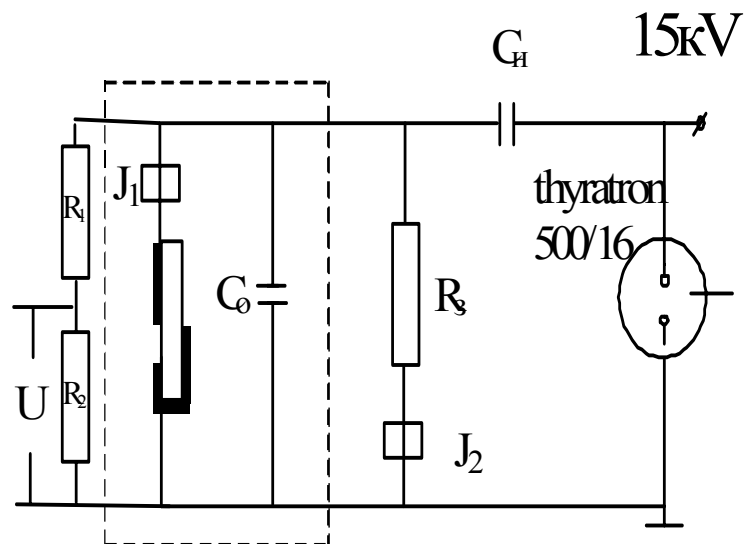
Internal aerodynamics:

- certification of gas discharges for applications in scramjets:
 - Plasma jets (stationary and pulsed)
 - Longitudinal and transversal gas discharges
 - High frequency and Microwave discharges (streamer, brush and surface discharges)
 - Sliding discharges

Scientific partnership

- MSU, TsAGI, CIAM, SDO “HORIZONT” in structure of “SALUTE”, MRTI

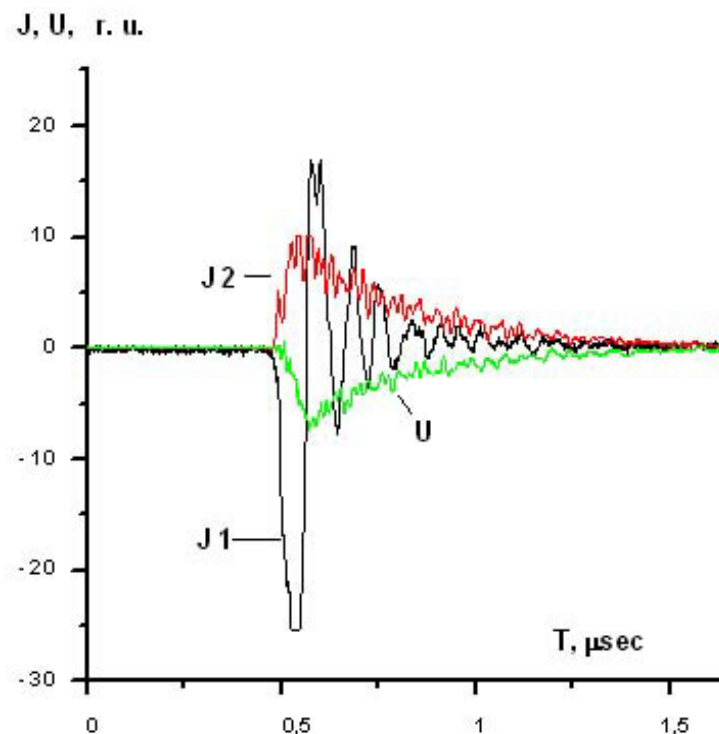
2. Sliding discharge for aerodynamics (continuation)



Electric scheme of Sliding discharge,

J_1, J_2 - Rogovsky coil,

R_1, R_2 -Voltage divider



Unfinished sliding discharge

**Ampere-Volt characteristics
in air, $p=1$ atm.**

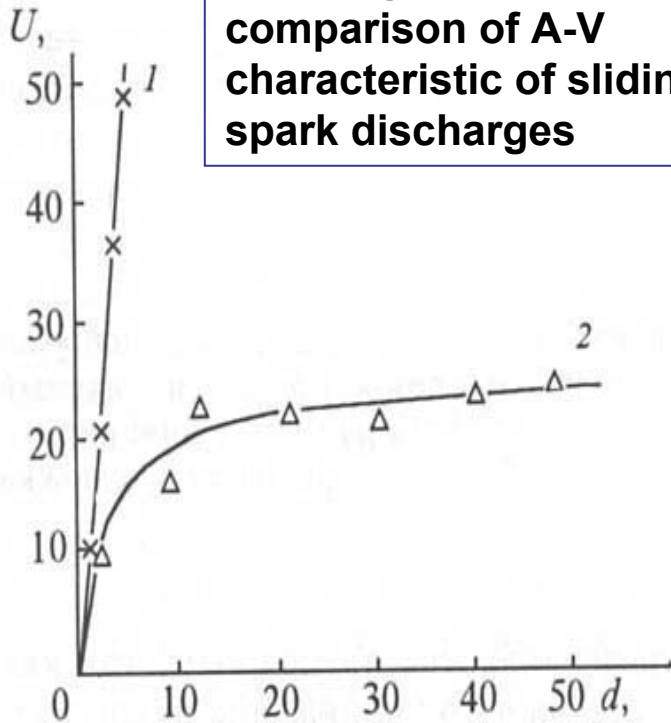
U - a voltage on the discharge gap,

J_1 - a current on the discharge gap

J_2 -a current on the charging resistance

Sliding discharge for aerodynamics (continuation)

Advantages of the sliding discharge are well seen from comparison of A-V characteristic of sliding and spark discharges



Sliding discharge appearance in the chamber at pressure $\sim 0,1$ atm.



Breakdown dependence on inter electrode gap: Air,
1 - Spark discharge,
2 - Sliding discharge

$p = 0,1 \text{ atm}$,
length - $l = 300 \text{ mm}$,
width - $h = 30 \text{ mm}$.

Sliding discharge for aerodynamics (continuation)

Aerodynamic models

Two model designs were developed for experiments in the wind tunnel A-7 NII Mech MSU (transonic: $M=0.4-4$, section 600×600 mm)

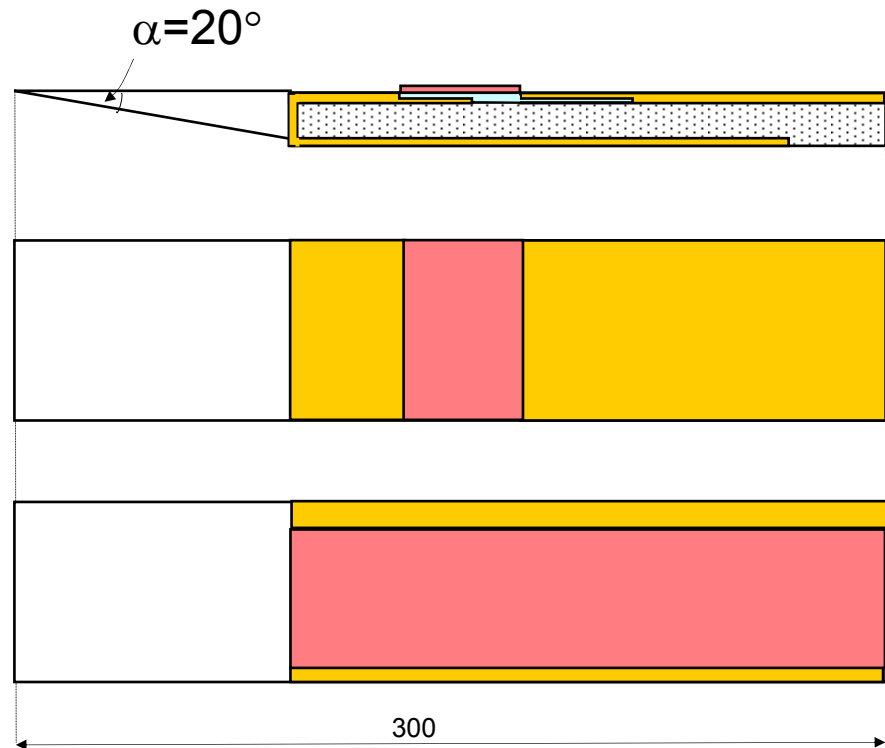
The first one is aimed for realization of the longitudinal (oriented along the flow) pulse - periodic sliding discharge, pulse duration $t \leq 1 \mu\text{s}$, pulse repetition rate – up to 2 kHz.

The second one is aimed for realization of the transversal (oriented perpendicular to the flow) pulse - periodic sliding discharge, pulse duration $t \leq 1 \mu\text{s}$, pulse repetition rate – up to 2 kHz.

Model bodies were made of dielectric material - the glass plates, electrodes were made of brass.

Typical model sizes are $(20 \div 100) \times 300 \times 30$ mm.

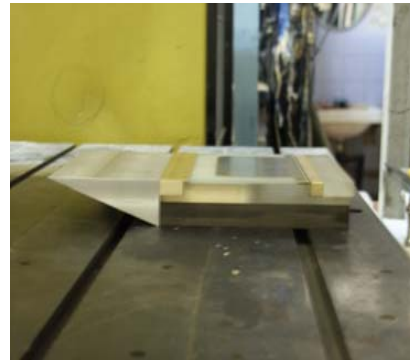
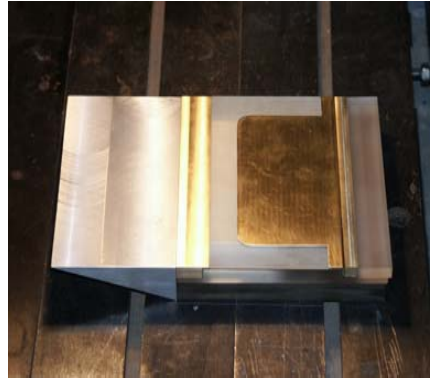
Schematics of the aerodynamic model



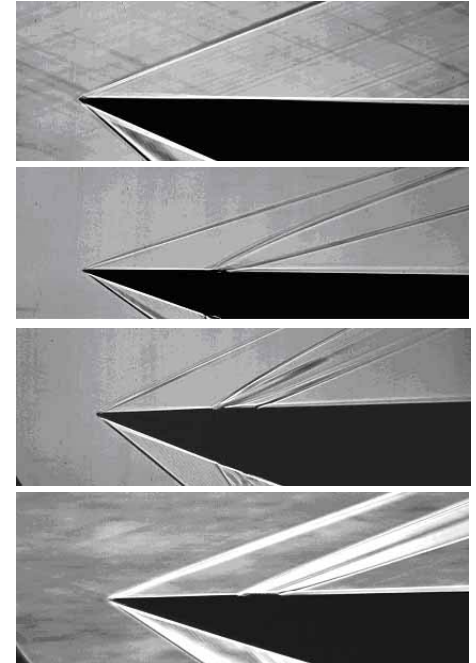
Sliding discharge for aerodynamics (continuation)



Sliding discharge application for improving of flight aerodynamics



Aerodynamic model



Visualizing of the boundary layer on a model (widening of the boundary layer)

Sliding discharge for aerodynamic (continuation)

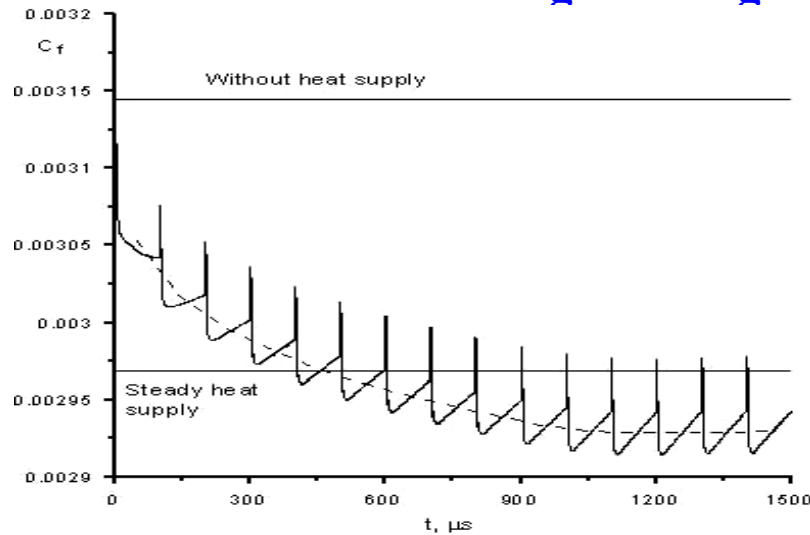
The sliding discharge influence on the gas flow was simulated by the non-steady near wall heat source with the specified space and time distributions intensity.

- Parametric calculations of the flow over flat plate for wind tunnel experiments conditions $M_\infty = 0.8$ (total pressure $p_0 = 1.2$ atm, and total temperature $T = 300$ K); and $M_\infty = 3$ (total pressure $p_0 = 3.7$ atm, and total temperature $T = 300$ K) were made. The effects of heat deposition on skin-friction and near wall flow structure were studied.
- The pulse-periodic heat deposition sliding discharge modeling has been made. At that the pulse length t_p was $1\mu s$, the form of pulses was triangular, pulse frequency f_p was 10 kHz , total heat supply during one pulse (cycle) was $Q_p = 10^{-2}\text{ J/cm}^2$.
- The simulation is based on the Favre averaged Navier-Stokes equations for thermally equilibrium chemical frozen air gas phase. Two-parametric differential k-omega turbulence model is used for the turbulence transfer description.
- Heat supply was distributed uniformly into the space region: $5 \leq x \leq 10\text{ cm}$, $0 \leq y \leq 0.1\text{ cm}$, where x, y are Cartesian coordinates attached to plate surface. This case heating distribution corresponds to the longitudinal sliding discharge.
- The skin-friction coefficient C_f for the plate section The value of C_f is defined by the expression

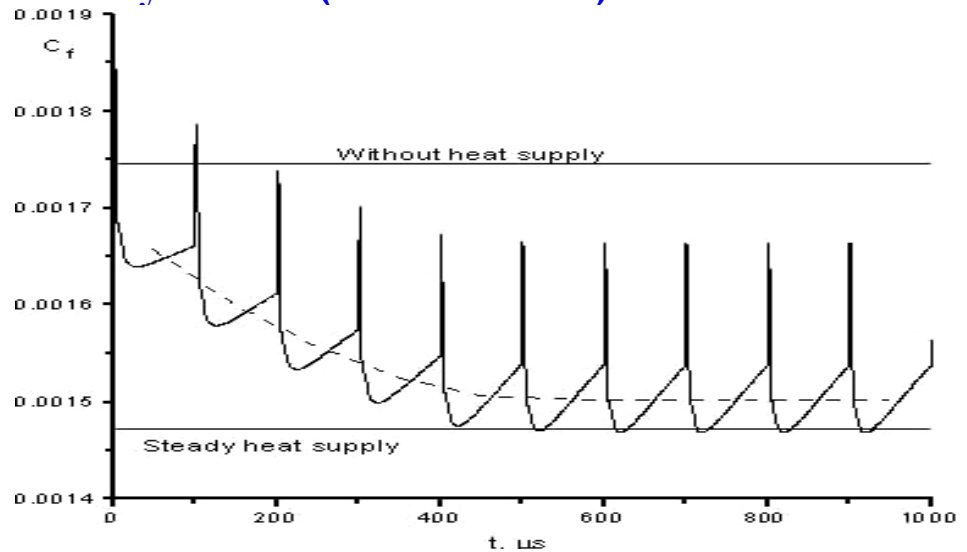
$$C_f = \int_{x_b}^{x_e} \tau_w dx / 0.5 \rho_\infty V_\infty^2 (x_e - x_b)$$

where τ_w is the local skin-friction, ρ_∞ and V_∞ are the free stream density and velocity respectively, $x_b = 0\text{ cm}$, $x_l = 30\text{ cm}$.

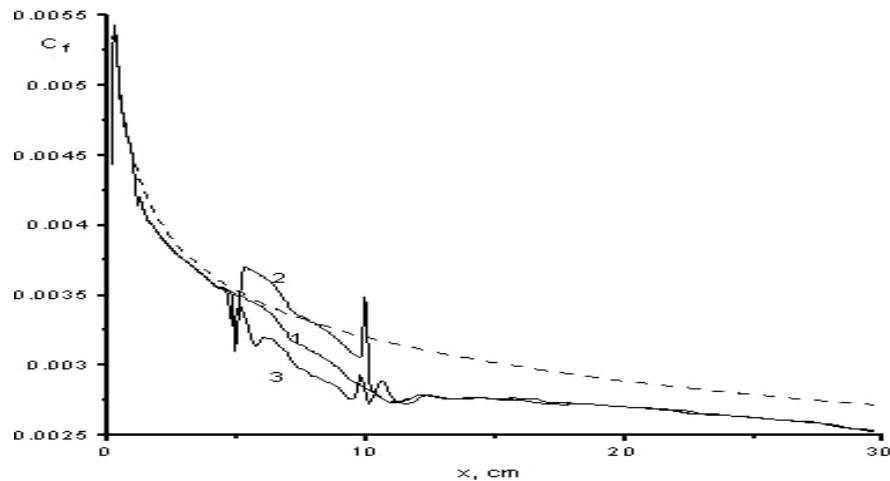
Sliding discharge for aerodynamics (continuation)



Time variation of total skin-friction coefficients at $M = 0.8$

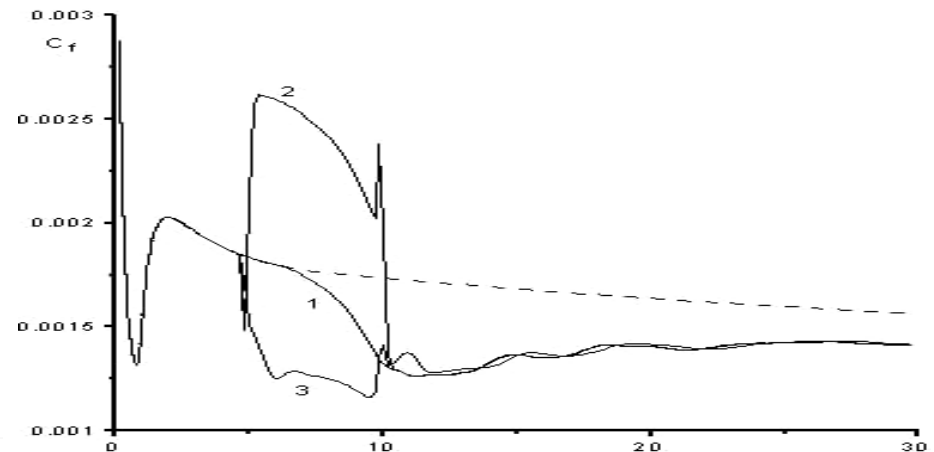


Time variation of total skin-friction coefficients at $M_\infty = 3.0$



Time history of local skin-friction distribution along the plate surface at $M_\infty = 0.8$.

$t = 1200 \mu s$, 2 - $t = 1201 \mu s$, 3 - $t = 1212 \mu s$



Time history of local skin-friction distribution along plate surface at $M = 3.0$

1 - $t = 800 \mu s$, 2 - $t = 801 \mu s$, 3 - $t = 812 \mu s$

Ignition of supersonic fuel flows in the supersonic channel with a help of gas discharges

We have made design works and manufacturing of the supersonic channel (scramjet model).

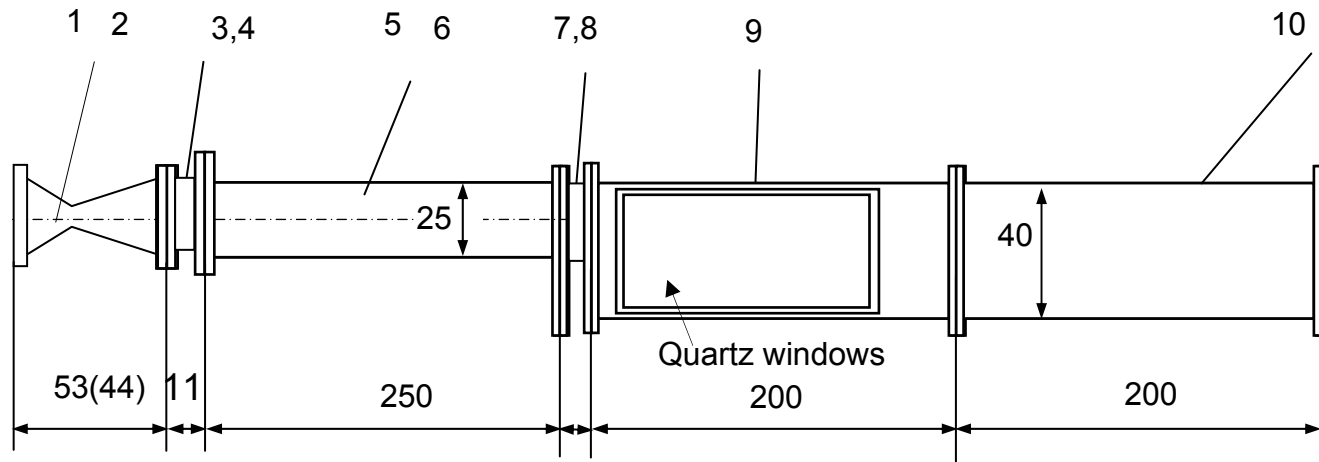
We suppose to put different plasma generators into the channel and to study their influence on the combustion initiation and combustion stabilization in the channel.

The channel sizes and materials for its manufacturing were determined on a basis of the following requirements to the channel :

- 1. for modeling of conditions corresponding to the Mach number $M=2$ at the inlet to the channel with $P_{\text{stat}}=0.25-0.6$ atm., total parameters of airflow:
 $P_{\text{tot}} = 2-10$ atm. and $T = 300 - 900$ K;
Time of stationary combustor work is no less than 5 s;**
- 2. supersonic nozzle for $M=2$ and the isolating channel element for the discharge were manufactured in flat and axisymmetric variants;**
- 3. optical quartz windows are foreseen in the region of the fuel mixture ignition for visualizing of the flow and the application of optical diagnostics;**

Ignition of supersonic fuel flows in the supersonic channel with a help of gas discharges (continuation)

Supersonic channel design



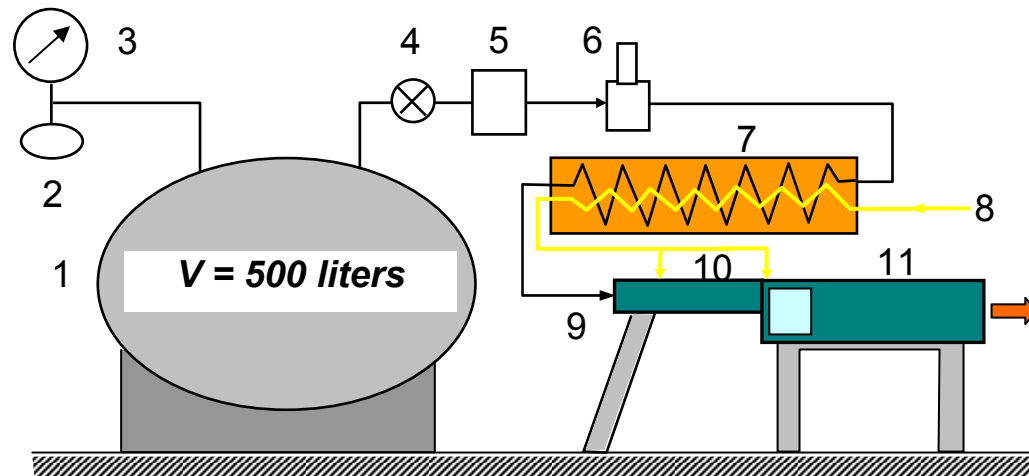
Channel scheme for combustion investigations

1,2 – supersonic nozzle $M=2$; 3,4 – collectors for preliminary fuel supply; 5-6 –flow stabilizing channel; 7, 8 – collectors of main fuel supply; 9 – 1-st part of the combustor, 10 – 2-nd part of the combustor

(sections «9» and «10» are manufactured in 2 copies and the total channel length can be changed from 730 to 1130 mm)

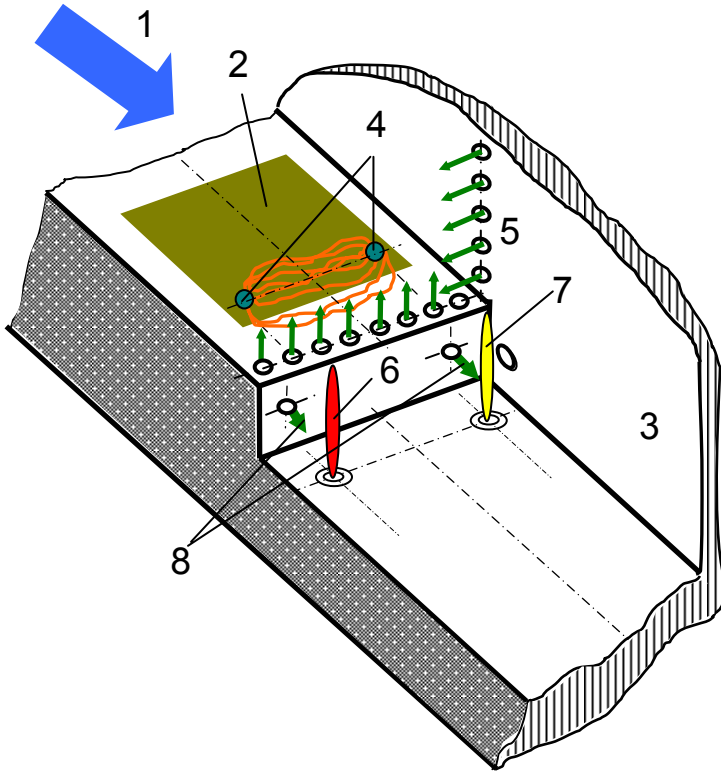
(linear sizes of channel sections of axisymmetric and flat configurations are equal with exception of the nozzle section «1», in frames the size of the axisymmetric channel scheme is indicated)

Ignition of supersonic fuel flows in the supersonic channel with a help of gas discharges (continuation)



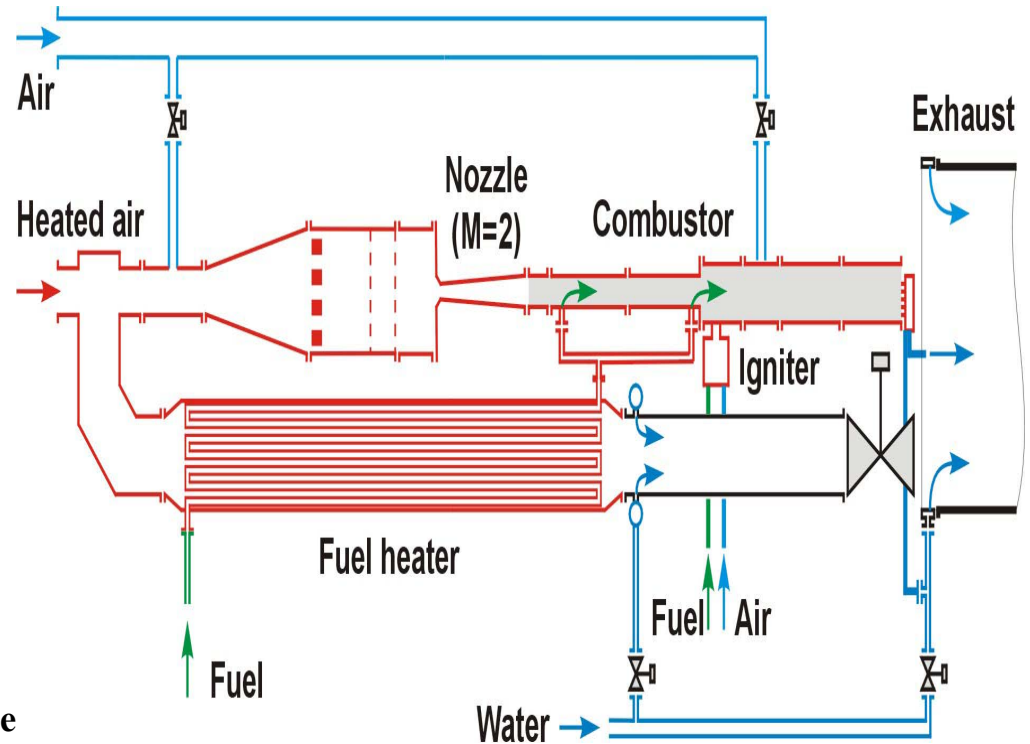
1 – balloon stage ($P_t \leq 12$ atm.), 2 – pressure regulator, 3 – manometer, 4 – valve,
5 – electrical valve, 6 – reduction gear, 7 – heater - thermostat, 8 – heating fuel section, 9
– air channel, 10 – system of the fuel delivery, 11 – measuring section

Ignition of supersonic fuel flows in the supersonic channel with a help of gas discharges (continuation)



Scheme of Plasma generator location in the combustor (upper and side walls are removed)

- 1 – supersonic air flow, 2 – dielectric insert,
3 – side wall, 4 – electrodes and transversal
discharge, 5 – wall fuel injection, 6- methane
air igniter, 7 – torch igniter,
8 – fuel injection into separation zones**



CIAM test rig scheme

Plasma sources

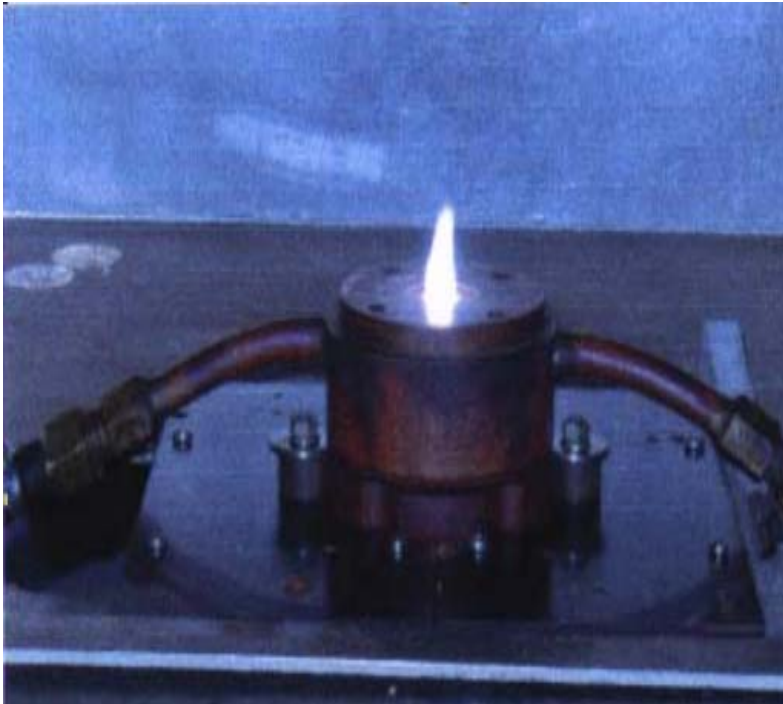
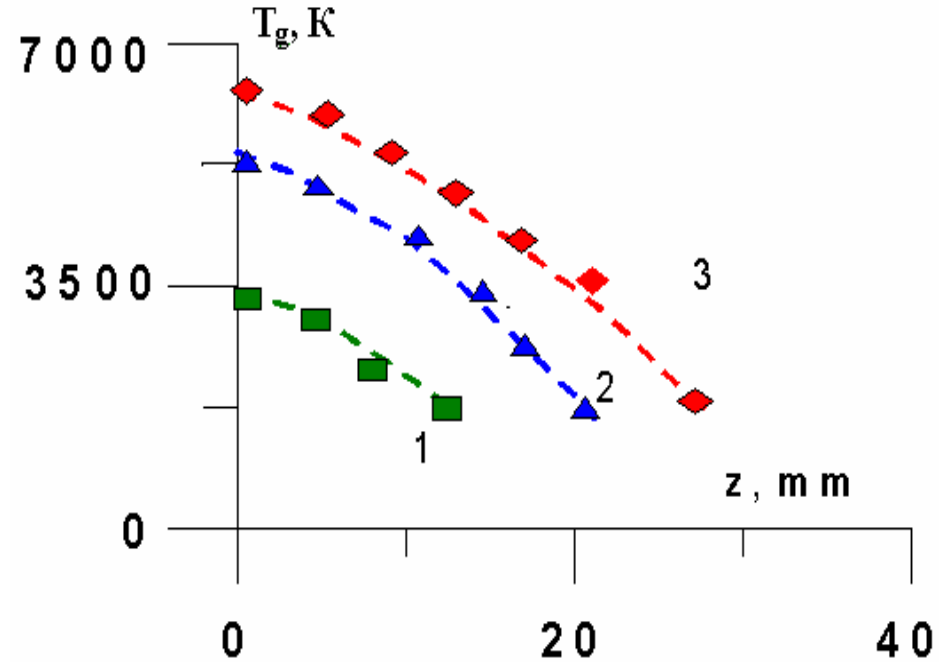


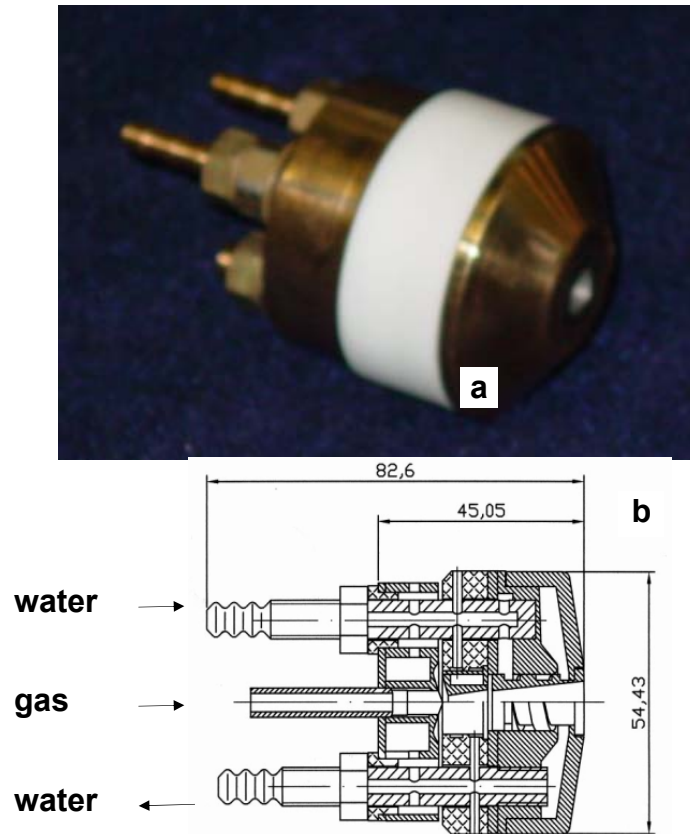
Photo of the stationary plasma jet
for the input power 6.5 kW.
 $P=1$ atm



Longitudinal distribution of the gas temperature of the nitrogen jet for the input power: $p=1$ atm.

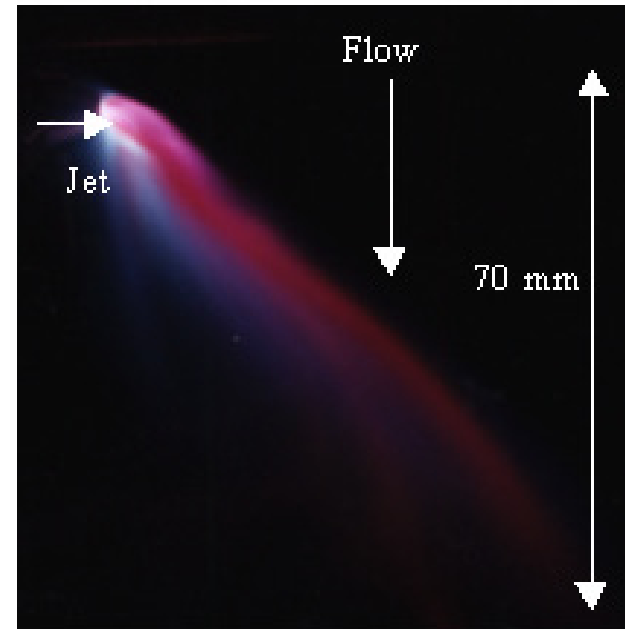
1 – 3 kW; 2 – 4,5 kW, 3 - 6,5 kW.

Plasma sources (continuation)



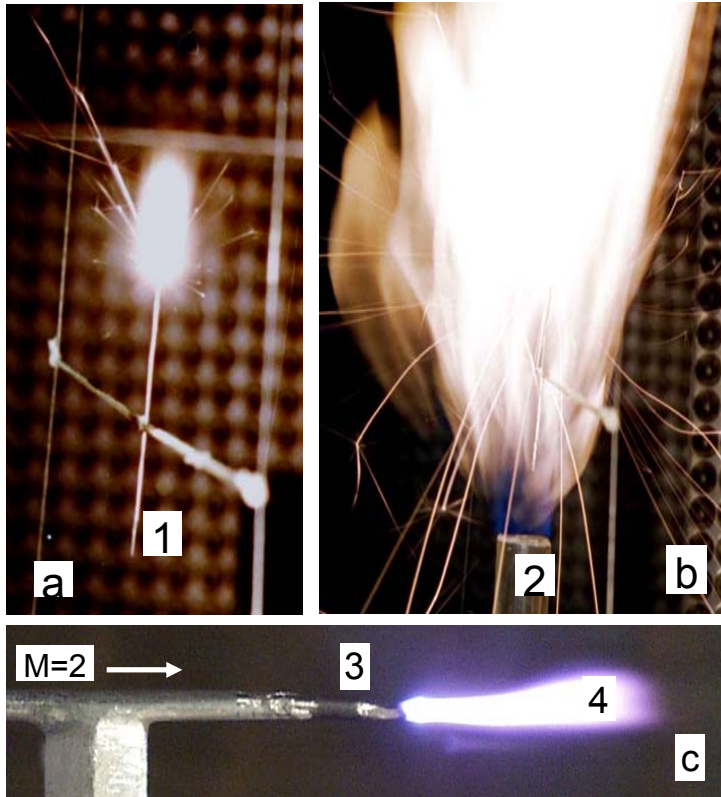
a – photo of the plasma generator with vortex stabilizing of the flow, plasma forming gas injection angle is $\alpha = 6^\circ$, the single contour system of water cooling,

b - Plasma generator drawing.



Appearance of pulse plasma jet interaction with a flow at 90° angle. Plasma jet velocity $V_{\text{jet}} \approx 850$ m/s, $T_{\text{jet}} \approx 6000$ K. Crossflow: $M=2$, $T=167$ K,

Plasma sources (continuation)



MW discharge initiated by the vibrator in air,
 $N \approx 1 \text{ kW}$, $p_{a,t} = 0.1 \text{ MPa}$, MRTI

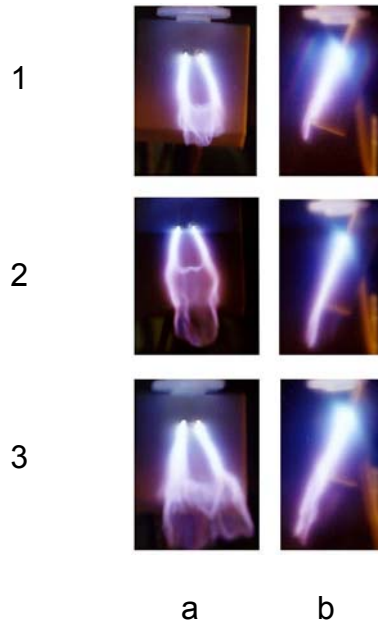
- a - without fuel,
- b - with propane supply,
- c - propane injection into supersonic flow
- 1 - vibrator, 2 - quartz tube for propane supply,
- 3 - vibrator installed on the pylon,
- 4 - propane flame



General view of the sliding discharge in the working chamber. MSU

$P = 0.001 \text{ MPa}$,
 discharge length - $L = 300 \text{ mm}$,
 discharge width - $s = 30 \text{ mm}$.

Plasma sources (continuation)

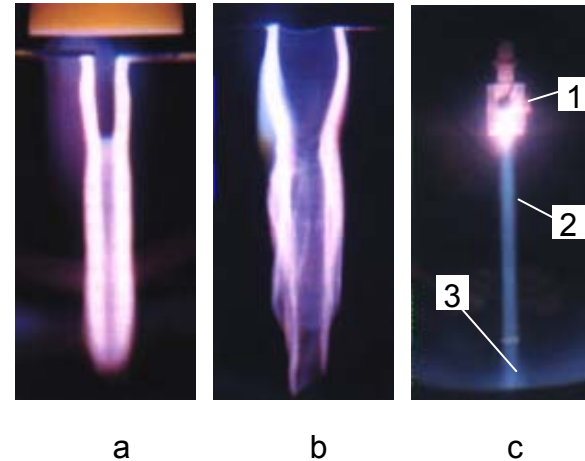


Surface pulse-periodic discharge in the supersonic airflow over the flat plate at different air pressures in the receiver p_o , atm:

1 - 1; 2 - 3; 3 - 6.

a - front view;

b - side view



Transversal gas discharge.

Mach number $M = 2$,

a – Constant current discharge, pressure $P_p = 1$ atm, $P_c = 40$ Torr, $I = 1,5$ A;

b - $P_p = 2$ atm, $P_c = 40$ Torr, $I = 20$ A, $\tau = 1000 \mu s$

c – fuel ignition :

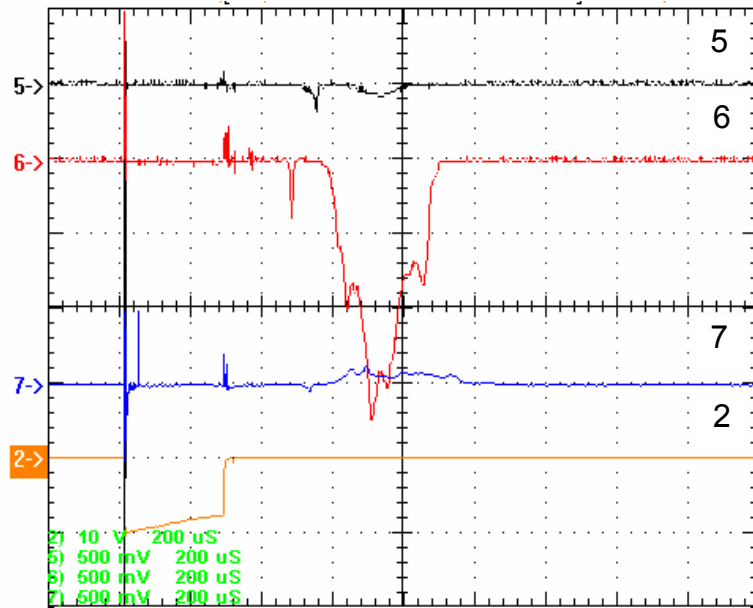
1 – discharge chamber,

2 – quartz channel,

3 – fuel combustion

Plasma sources (continuation)

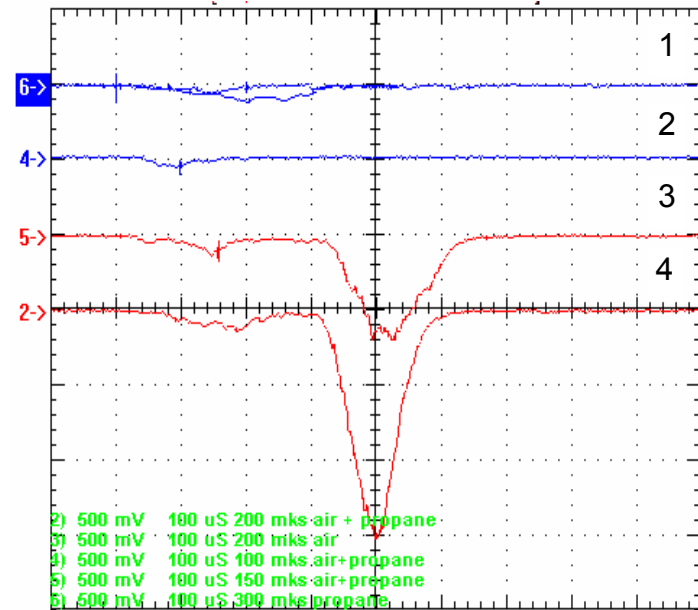
Fuel combustion in direct - flow supersonic channel: Diagnostics



Probe currents of the transversal discharge supersonic propane/air mixture flow by pulse $\tau = 300 \mu\text{s}$, $P_{a,t} = 0.3 \text{ MPa}$, $p = 200 \text{ Torr}$.

Probe bias $U = \pm 100 \text{ V}$ for electron and ion current consequently,

$R_m = 1 \text{ k}\Omega$,
probe position $X \approx 32 \text{ cm}$.



Waveforms of plasma luminescence (431.5 nm, CH) in the pulsed transversal discharge in the supersonic flow of air, propane and the air-propane mixture.

$P_{a,t} = 0.4 \text{ MPa}$, $p = 200 \text{ Torr}$, $I = 20 \text{ A}$, $X = 25 \text{ cm}$.

1 - air, 200 μs ; propane, 300 μs ;

2 - air + propane, 100 μs ;

3 - air + propane, 150 μs ;

4 - air + propane, 200 μs ;

Plasma sources (continuation)

MW plasma jet MSU and General Physics Institute



- **$N = 0.8$ kW**
- **$P \leq 0.1$ MPa**
- **Working gases – argon, nitrogen, propane**
- **$G=50$ litre/min**
- **Connection dimensions correspond to the connection units in MSU combustor**

Conclusions

During last two years the following works were realized in frames of works with EOARD :

- 1. Theoretical and experimental investigations of plasma jet interaction with air and propane-air flows, Project ISTC # 2449-p;**
- 2. Theoretical and experimental investigations of sliding discharge has been made, Project CRDF # RPO-1382**
- 3. Aerodynamic models of sliding discharge for experiments in wind tunnel A-7 has been made. Sliding discharge parameters in air have been investigated, pilot blow-throughs in wind tunnel A-7 have been made for visualizing of the boundary layer, Project CRDF # RPO-1382**
- 4. The supersonic combustor has been developed, manufactured and completed by the diagnostic equipment, Project CRDF # RCO-1383**

Prospects

1. Development of theoretical models of plasma-jet cross flow air-fuel mix interaction for optimization of combustion modes.
2. Experimental investigations of plasma-jet cross flow air-fuel mix interactions.
3. Investigation of the sliding discharge influence on the boundary layer structure and surface friction.
4. Optimization of sliding discharge sources work with respect to energy losses.
5. Analysis of sliding discharge applicability for fuel ignition in the supersonic channel (preliminary results has been obtained).
6. Development of works on ignition and combustion stabilization of hydrocarbon fuels in the supersonic combustor.
7. Scaling works on plasma aerodynamic experiments

Acknowledgments

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